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# BIBLIOGRAPHY ON CERAMIC MATRIX COMPOSITES AND REINFORCING WHISKERS, PLATELETS, AND FIBERS 1970 - 1990

CIAC SPECIAL REPORT 2

August 1993



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This report contains bibliographic information on pertinent documents dealing with ceramic matrix composites (CMCs) and reinforcing whiskers, platelets, and fibers in the period 1970 to 1990. The report is organized into three broad categories. The first category presents bibliographies on the processing methods and properties of various types of reinforcements. The second category constitutes the bulk of the report. This section is divided into seven parts, each being concerned with a particular type of ceramic matrix material, such as borides, carbides, nitrides, oxides, glasses, and glass-ceramics. Within each matrix material, there are further categories sorted by the reinforcement used, e.g., fibers, whiskers, platelets, particulates, etc. The final section of the report contains bibliographies of articles discussing the theories of reinforcement, processing, testing and test methods, as well as certain applications for ceramic matrix composites.

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# PREFACE

This CIAC Special Report contains bibliographic information on pertinent documents dealing with ceramic matrix composites and reinforcing whiskers, platelets, and fibers published in the period 1970 to 1990. The report is prepared and published by the Ceramics Information Analysis Center (CIAC), a U.S. Department of Defense (DoD) Information Analysis Center. CIAC was established on August 16, 1990, as one of two new DoD information analysis centers, replacing the Metals and Ceramics Information Center (MCIC) operated before August 1990 by Battelle Columbus Division, Battelle Memorial Institute, Columbus, Ohio.

CIAC, a DoD Information Analysis Center, is sponsored and administratively managed and funded by the Defense Technical Information Center (DTIC), ATTN: DTIC-AI, Cameron Station, Alexandria, VA 22304-6145, and is under the IAC program management of Dr. Forrest R. Frank. It is operated by the Center for Information and Numerical Data Analysis and Synthesis (CINDAS), Purdue University, West Lafayette, Indiana 47906 under Contract DLA900-90-D-0304. The contract was awarded to Purdue Research Foundation by the Defense Electronics Supply Center (DESC), Dayton, Ohio 45444-5208 with Ms. Cheryl A. Montoney as the contracting officer. CIAC is under the technical direction of Mr. Jerome Persh, Staff Specialist for Materials and Structures, Office of the Director of Defense Research and Engineering (Advanced Technology), ATTN: ODDR&E (AT), The Pentagon, Room 3D1089, Washington DC 20301-3080.

CIAC is a Full-Service DoD Information Analysis Center and has been well oriented to the needs of its users community. It searches, identifies, acquires, collects, reviews, analyzes, appraises, summarizes, computerizes, stores, and provides timely information and data, and advisory, analysis, and other services concerning the available worldwide scientific and technical information and engineering data on ceramic materials that are important to the DoD.

CIAC serves as the DoD's central source of engineering and technical data and research and development information on monolithic ceramics and ceramic composites, hybrids, laminates, and coatings utilized in Defense systems and hardware. Data and information on reinforcing fibers and whiskers, composite joints, and non-structural composites such as piezoelectric-ceramic materials, superconducting ceramics, and optical materials are also covered. Emphasis is placed on those ceramics and ceramic composites and coatings used in critical structural and thermal applications and/or in other stringent environments.

Subject areas covered include ceramics properties (especially mechanical properties as a function of composite architecture, temperature, and environmental conditions); latest research and development

concepts, results, and trends; applications and processing of ceramics; processing equipment; measurement and testing of ceramics; test methods; quality control related to ceramics; corrosion/deterioration detection, prevention and control, and other environmental effects on ceramics and systems; producers, suppliers, and specifications for ceramics of concern to the DoD.

CIAC supports the Joint Logistics Commanders/Joint Directors of Laboratories Technology Panel for Advanced Materials, and provides assistance to or receives guidance from other Defense Programs and Groups as designated by the Technical Monitor.

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# INTRODUCTION

This bibliography report updates previously published reports[1, 2] by the Metals and Ceramics Information Center (MCIC) operated before August 1990 by Battelle Columbus Division, Battelle Memorial Institute, Columbus, Ohio.

Ceramic Matrix Composites (CMCs) represent a class of advanced composite materials that are essential for many current and future military, aerospace, and commercial applications. Much progress has been made during the past years toward understanding various aspects of CMCs and their reinforcing constituents. Technical data and information on processing, fabrication, characterization, interfacial, and microstructural properties, new analytical tools, new procedures, mechanical testing, etc., of CMCs are being generated worldwide at a rapid rate. Consequently, it was deemed useful to update the MCIC bibliographic reports and present the bibliographic citations in a much improved and organized manner focusing on CMCs and their reinforcements.

CMCs are, for the most part, made of ceramic materials (matrices) such as alumina, silicon carbide, silicon nitride, glass, and glass-ceramic, reinforced with continuous fibers, chopped fibers, short discontinuous whiskers, platelets, particulates, and mixtures thereof. Examples of reinforcements are glass fibers, silicon carbide fibers, silicon nitride whiskers, silicon carbide whiskers, and silicon carbide platelets. The ultimate goal in composite fabrication is to produce a material that possesses desirable properties that are not achievable by the individual components alone.

CMCs can generally be categorized according to their failure mode and processability. Although whisker-, particulate-, and platelet-reinforced CMCs are relatively easy to process and provide enhanced toughness, they do not eliminate the possibility of catastrophic failure due to the fact that their properties are still matrix-dominated. Continuous-fiber ceramic matrix composites, on the other hand, tend to fail non-catastrophically. If fiber lay-up architecture and fiber/matrix interfacial bonding are optimized so that mechanical behavior is fiber-dominated, then rapid crack propagation through the matrix will not lead to catastrophic failure.

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[1, 2] *Bibliography on Fibers and Composite Materials - 1969-1972*, MCIC Report 72-09 (July 1972). Distributed by DoD Ceramics Information Analysis Center (CIAC).

*Bibliography on Fibers and Composite Materials - 1972-1978*, MCIC Report 78-38 (October 1978). Distributed by DoD Ceramics Information Analysis Center (CIAC).

Generally speaking, particulate- and whisker-reinforced CMCs are potential commodity materials for armor, cutting tools, and automotive engine components whereas fiber-reinforced CMCs are materials for aerospace vehicles, propulsion components, space structures and other military applications. Fiber-reinforced cements and concretes have great potential for low cost, broad applications for large structures such as runways, carrier decks, nuclear blast-resistant buildings, etc.

This report covers the period from 1970 to 1990. The main focus of the report is on CMCs and their reinforcements; polymer matrix, metal matrix, and carbon/carbon composites are not covered in this report.

In general, the report is organized as follows:

**Reinforcements**

This section is organized into three broad categories. The first presents bibliographies of papers whose main focus is on the properties and processing methods of each type of reinforcement available to CMCs. This section is further grouped by the type of material used as the reinforcement. The materials listed in this report include borides, carbides, nitrides, and oxides, as well as glass and glass-ceramic reinforcing constituents.

**Ceramic Matrix Composites**

The second category constitutes the bulk of this report. This section is divided into seven parts, each being concerned with a particular type of ceramic matrix material. These are oxides, carbides, nitrides, etc. Within each matrix material, there are further categories sorted by the reinforcement used, e.g., fibers, whiskers, platelets, particulates, etc.

**General Topics**

The final section of this report contains bibliographies of articles discussing the theories of reinforcement, processing, testing and test methods, as well as certain applications for ceramic matrix composites. Generally, no specific materials are mentioned in these citations.

Certain documents listed within this report deal with topics which the U. S. Government considers sensitive to widespread distribution. These documents are footnoted in this report as limited distribution or export control as defined below.

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Transmittal of these documents outside of U.S. Government agencies and their contractors must have prior approval of the controlling DoD office.

# 1. REINFORCEMENTS

## 1.1 Borides

### *1.1.1 Fibers*

1.1.1.1
**Very High Temperature Fibers of TiC and $TiB_2$**
Schlecht, R. G.
Lasergenics Corporation, San Jose, CA
Final Report, April 88-August 90
1991
( AD A237 423 )

1.1.1.2
**Synthesis of High-Performance Ceramic Fibers for Specialized Applications**
Hlavacek, V. Arya, Prakash V.
Revankar, Vithal
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NASA Langley Research Center, Hampton, VA
Conference Publication
Metal Matrix, Carbon, and Ceramic Matrix Composites 1988
NASA-CP-3018, 29-47, Nov 1988
( AD D250 837 ) *

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**High Strength and Modulus Filaments of Boron and Silicon Carbide**
Buck, M. E.
Mater. Des.
8 (5), 272-7, 1987
( AD D137 812 )

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**Growth and Mechanical Properties of the Whiskers of Boron and Some Borides**
Ahmad, I.
Watervliet Arsenal, NY
WVT-6820, 81pp., 1968
( AD 756 400 )

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**Thermal Expansion of High-Modulus Fibers**
Hillmer, N. J.
Int. J. Thermophys.
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**Progress in $TiB_2$ Fiber Development**
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Henze, T. Krutenat, R.
Scaringella, D. Suplinskas, R.
Wawner, F. E.
NASA Langley Research Center, Hampton, VA
Edited by J. D. Buckley
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NASA-CP-3097, Part 1, 73-88, Dec 1990
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**Ceramic Fiber Composites for Electronic Packaging: Thermal Transport Properties**
Zhang, Hongmei Onn, David G.
Bolt, John D.
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Mater. Res. Soc. Symp. Proc.
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**Boron and Silicon Carbide/Carbon Fibers**
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Fibre Reinforcements for Composite Materials
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2 (Chapt. 8), 371-425, 1988
( AD D252 443 )

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**Fibers for Structurally Reliable Metal and Ceramic Composites**
DiCarlo, J. A.
J. Met.
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**High Performance Fibers for Structurally Reliable Metal and Ceramic Composites**
DiCarlo, J. A.
NASA Lewis Research Center, Cleveland, OH
1984
( AD D131 800 )
Prepared for Conference on High Performance Textiles Structures, cosponsored by The Fiber Society and SAMPE, Philadelphia, PA
June 6-8, 1984

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**Axial Residual Stresses in Boron Fibers**
Behrendt, D. R.
NASA Lewis Research Center, Cleveland, OH
N78-19204, NASA-TM-73894, 18pp., 1978
( AD D112 952 )
Presented at the 2nd International Conference on Composite Materials, Toronto, Canada, 16-20 Apr 1978

1.1.1.12
**Techniques for Increasing Boron Fiber Fracture Strain**
DiCarlo, J. A
NASA Lewis Research Center, Cleveland, OH
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**Changes in Boron Fiber Strength Due to Surface Removal by Chemical Etching**
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1.1.1.14
**Tensile Strength and Crack Nucleation in Boron Fibres**
Boggio, J. V. Vingsbo, O.
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( AD D102 532 )

*1.1.2 Ribbons*

1.1.2.1
**Development of a Process for Producing Ribbon Shaped Boron Filaments**
Basche, M. Jacob, B.
NASA Langley Research Center, Hampton, VA
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N74-13201, 35pp., 1974
( AD D104 293 )

1.1.2.2
**Development of a Process for Producing Ribbon Shaped Filaments**
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N74-10548, 38pp., 1973
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**The Microstructure of SCS-6 SiC Fiber**
Ning, X. J. Pirouz, P.
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6 (10), 2234-48, Oct 1991
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**TiC Reinforcements with Controlled Morphology**
Crouch, H. Steven Wright, Steve
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**Silsesquioxane-Derived Ceramic Fibres**
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Terepka, F. M. Leonhardt, T. A.
J. Mater. Sci.
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Casey, J. D Honig, E.
Krutenat, R. Suplinskas, R
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1.2.1.5
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Teusel, I. Russel, C.
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( AD D250 196 )

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**Mechanism of Pyrolysis of Amorphous Silicon Carbide Fibre Obtained from Polycarbosilane as Precursor**
Shimoo, Toshio Sugimoto, Masaki
Okamura, Kiyohito
Nippon Kinzoku Gakkaishi (J. Jpn. Inst. Met.)
54 (7), 802-8, 1990
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Borm, Jutta
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**Synthesis of Continuous Silicon Carbide Fibre. Part 6: Pyrolysis Process of Cured Polycarbosilane Fibre and Structure of SiC Fibre**
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**Effect of Curing Conditions on Mechanical Properties of SiC Fibre (NICALON)**

Ichikawa, H. Teranishi, H.
Ishikawa, T.
J. Mater. Sci. Lett.
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**Pressure Effects on the Thermal Stability of SiC Fibers**

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**Improved Fiber-Reinforced SiC Composites Fabricated by Chemical Vapor Infiltration**

Stinton, D. P. Caputo, A. J.
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**Preparation of Silicon Carbide-Silicon Nitride Fibers by the Pyrolysis of Polycarbosilazene Precursors**

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N85-28107, NASA-TM-86505, 11pp., 1985
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**Silicon Carbide Filaments: Microstructure**

Nutt, S. R. Wawner, F. E.
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# 2. REINFORCED OXIDE MATRICES

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# 3. REINFORCED CARBIDE MATRICES

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### *3.3.1 Fiber Reinforced*

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### *3.4.1 Fiber Reinforced*

3.4.1.1
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### *3.5.1 Platelet Reinforced*

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3.5.2.1
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Babonneau, Florence Soraru, Gian D
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### *3.6.1 Fiber Reinforced*

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# 4. REINFORCED NITRIDE MATRICES

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### *4.1.1 Fiber Reinforced*

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Kimura, I. Hotta, N.
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**Tribological Properties of Ceramic Materials Based on Nonmetallic Nitrides II. Effect of Oxide Films on the Process of Friction in the System Ceramic Material-Steel**

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## 4.2 BN Matrix

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## 7.5 Platelet Reinforced

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# 9. GENERAL TOPICS ON CMC's AND THEIR REINFORCEMENTS

## 9.1 Ceramic Reinforcements

### *9.1.1 Fibers*

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